Coherent electron cooling - perfect tool for high luminosity RHIC and eRHIC

Vladimir N. Litvinenko

C-AD, Brookhaven National Laboratory, Upton, NY, USA

BROOKHAVEN NATIONAL LABORATORY

RHIC

Intro

A bit of history

Principles of CEC

Analytical estimations

Simulations

Proof of Principle test using R&D ERL

In collaboration with

Yaroslav S. Derbenev

Thomas Jefferson National Accelerator Facility,

Newport News, VA, USA

And so, my fellow Americans, ask not what your country can do for you; ask what you can do for your country.

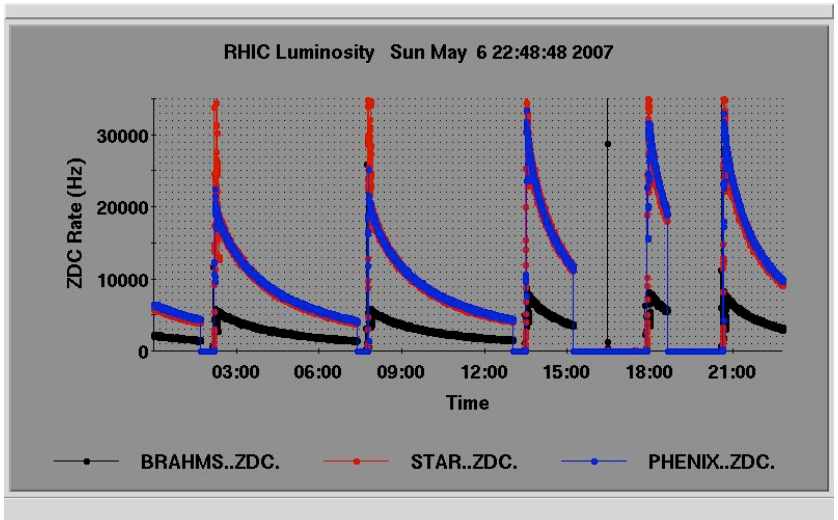
Measure of Performance

In Colliders - Luminosity

$$\dot{N}_{events} = \sigma_{A \to B} \cdot L \qquad L = \frac{f_{coll} \cdot N_1 \cdot N_2}{4\pi\beta^* \varepsilon}$$

Main sources of luminosity reduction
emittance growth and loss of particles

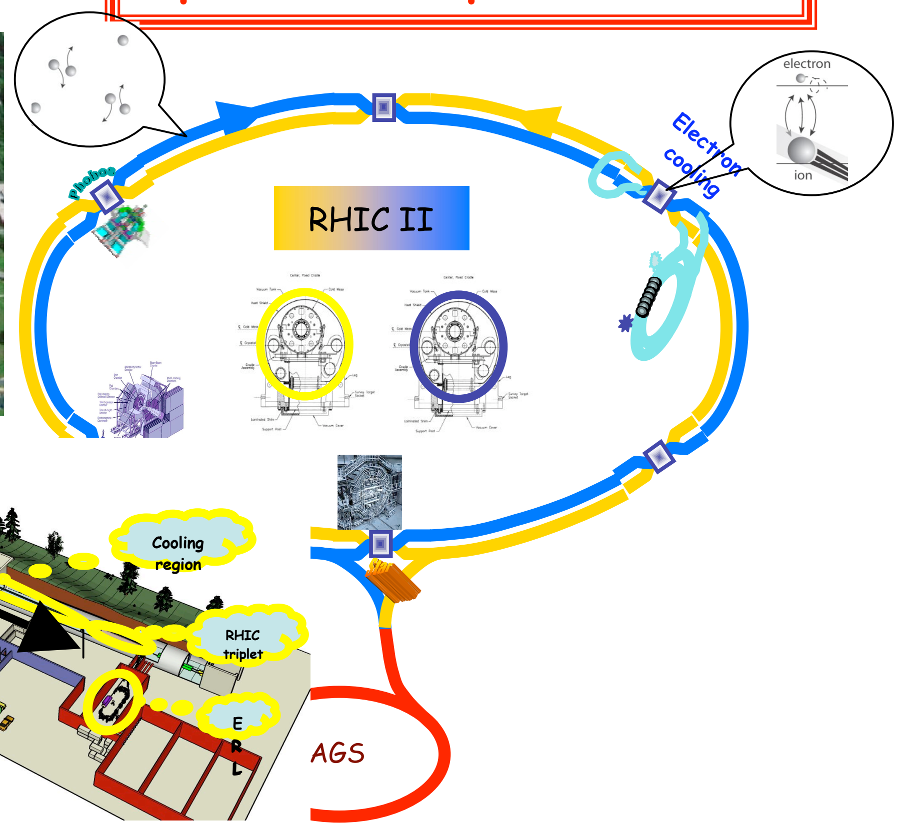
from the talk at International FEL conference, Novosibirsk, Russia, August, 2007

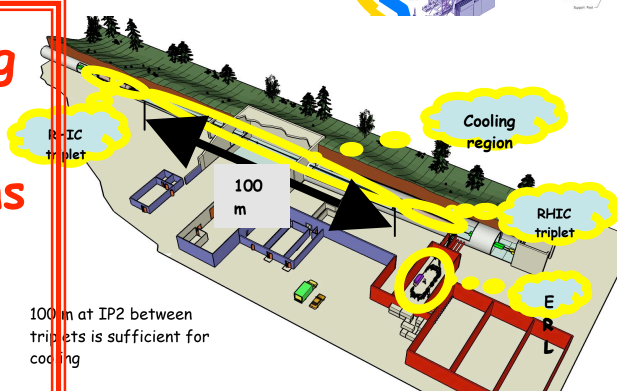


And so, my fellow FELers, ask not what storage ring can do for FELs;
Ask what FELs can do for your storage rings!

C-AD at BNL: home of RHIC and eRHIC

Traditional e-Cooling efficiency falls as $\gamma^{-7/2}$ and $\sim Z^2/A$
Very high energies and protons are problematic!



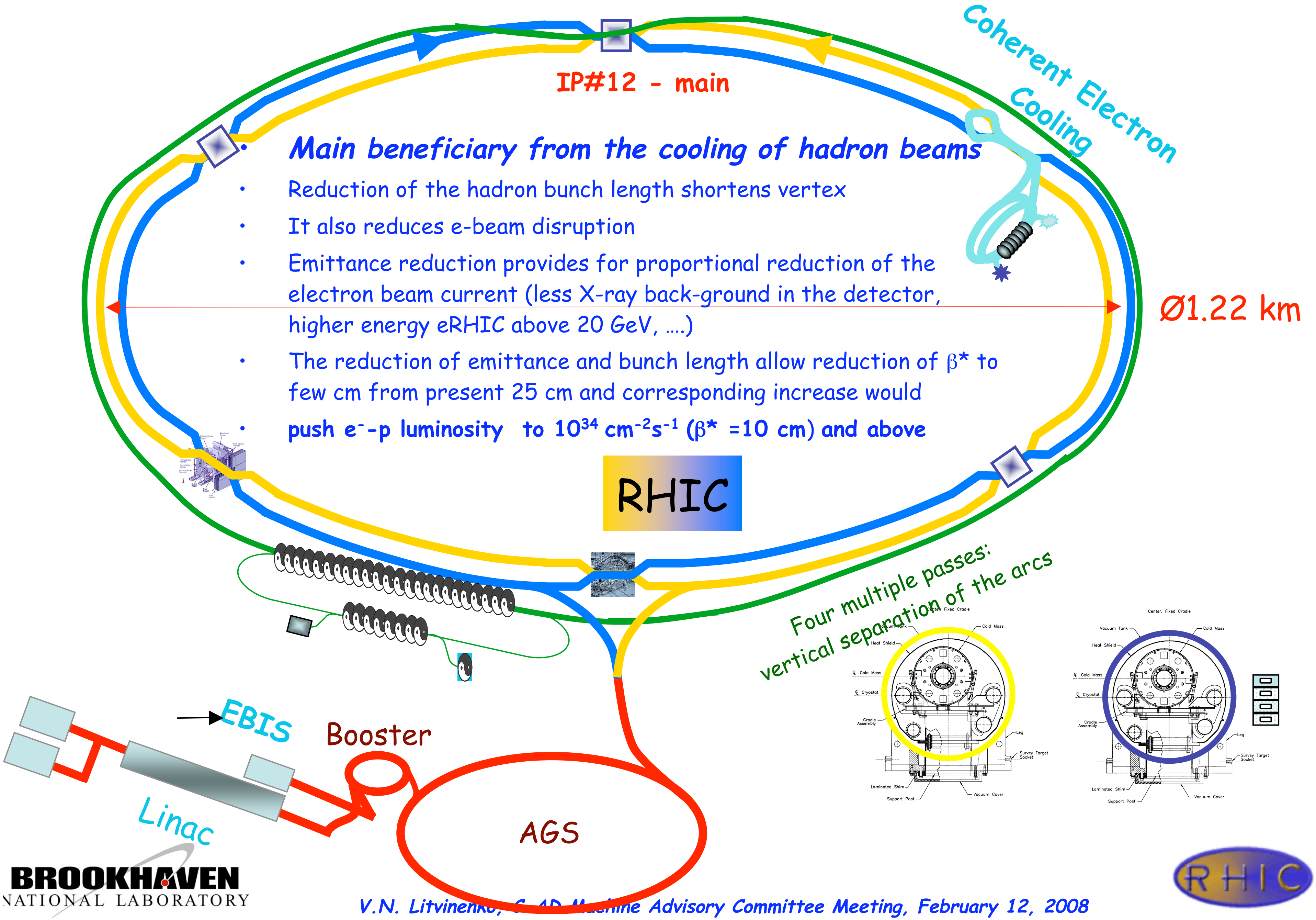


Traditional stochastic cooling falls as $1/N_p$ and 10^{11} protons per nsec bunch means $>10^{11}$ turns to cool them
$\sim 10^6$ sec for RHIC
Tevatron
$\sim 10^7$ sec for LHC

eRHIC based on 5-20+ GeV ERL

Main beneficiary from the cooling of hadron beams

- Reduction of the hadron bunch length shortens vertex
- It also reduces e-beam disruption
- Emittance reduction provides for proportional reduction of the electron beam current (less X-ray back-ground in the detector, higher energy eRHIC above 20 GeV, ….)
- The reduction of emittance and bunch length allow reduction of β^* to few cm from present 25 cm and corresponding increase would
- **push e^--p luminosity to 10^{34} $cm^{-2}s^{-1}$ (β^* =10 cm) and above**



BROOKHAVEN NATIONAL LABORATORY

RHIC

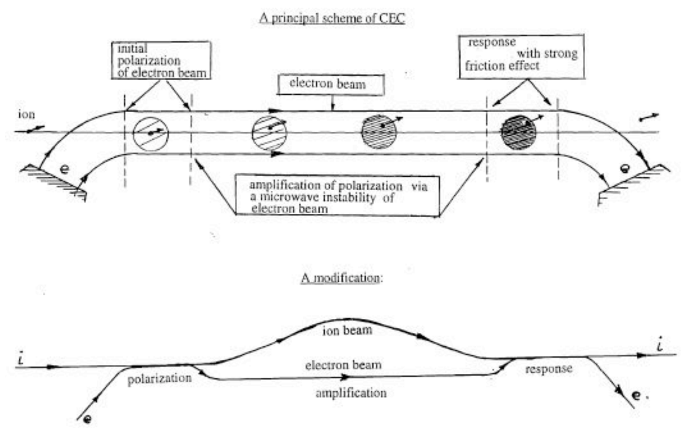
Cooling of hadron beams with coherent electron cooling

Machine	Species	Energy GeV/n	SC, hrs	Synchrotron radiation, hrs	Electron cooling, hrs	CEC, hrs
RHIC	Au	100	~1	20,961 ∞	~ 1	0.03
RHIC	p	250	~100	40,246 ∞	> 30	0.8
LHC	p	450	?	48,489 ∞	> 1,600	0.95
LHC	p	7,000	?	13/26	∞ ∞	< 2

History of idea:

coherent electron cooling was suggested by Yaroslav Derbenev about 26 years ago

- Y.S. Derbenev, Proceedings of the 7th National Accelerator Conference, V. 1, p. 269, (Dubna, Oct. 1980)
- Coherent electron cooling, Ya. S. Derbenev, Randall Laboratory of Physics, University of Michigan, MI, USA, UM HE 91-28, August 7, 1991
- Ya.S.Derbenev, Electron-stochastic cooling, DESY , Hamburg, Germany, 1995 ……….

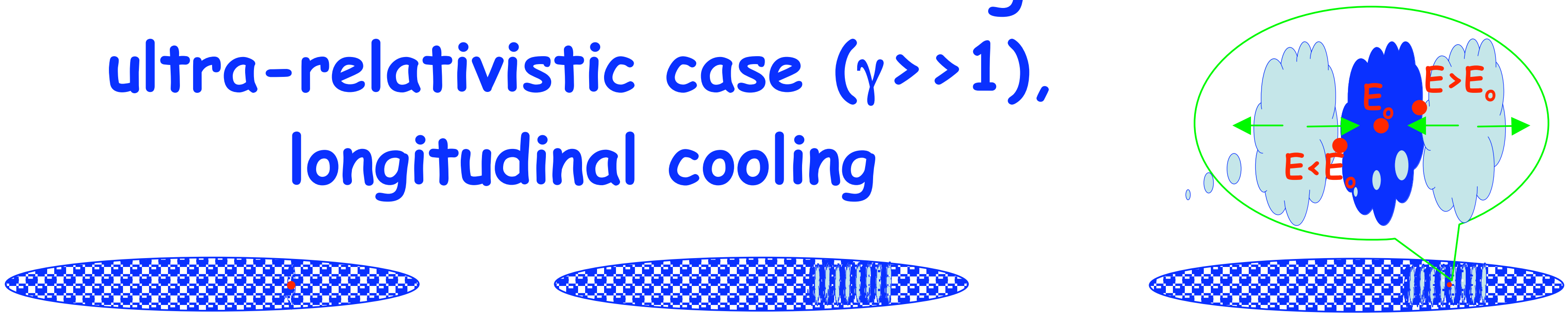


Q: What changed in last 25 years?

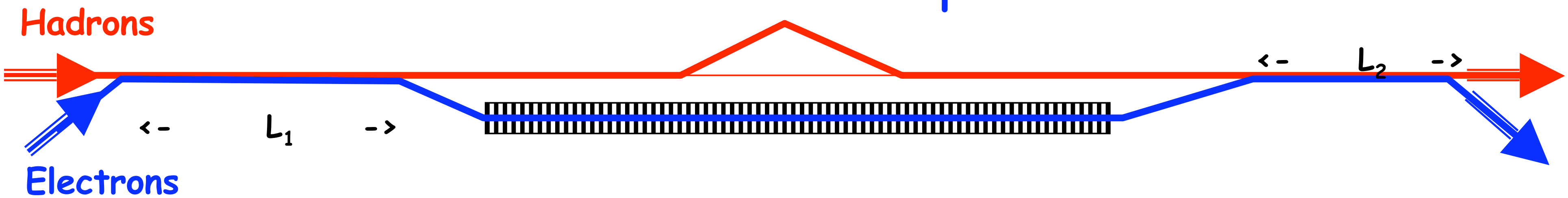
A: Accelerator technology caught up with the idea

- high gain amplification at optical (μm and nm) wavelengths became reality

Coherent electron cooling: ultra-relativistic case (γ>>1), longitudinal cooling



Most versatile option



Modulator:region 1
about a quarter of plasma oscillation

Longitudinal dispersion for hadrons

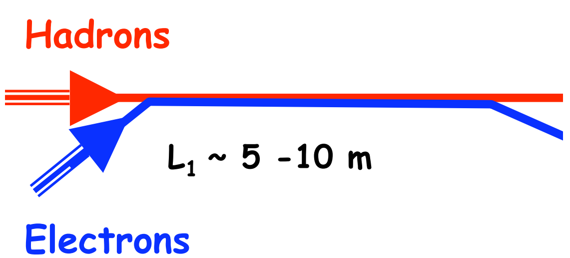
Kicker: region 2

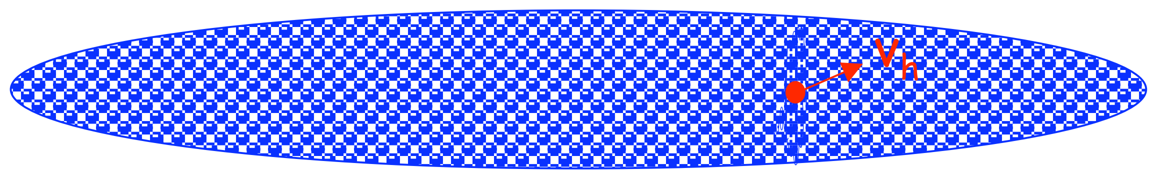
Amplifier of the e-beam modulation via High Gain FEL

Most economical option

Modulator: Interaction region 1
Length: about a quarter of plasma oscillation

$$\omega_{pe} = \sqrt{\frac{4\pi n_e e^2}{m_e}}$$





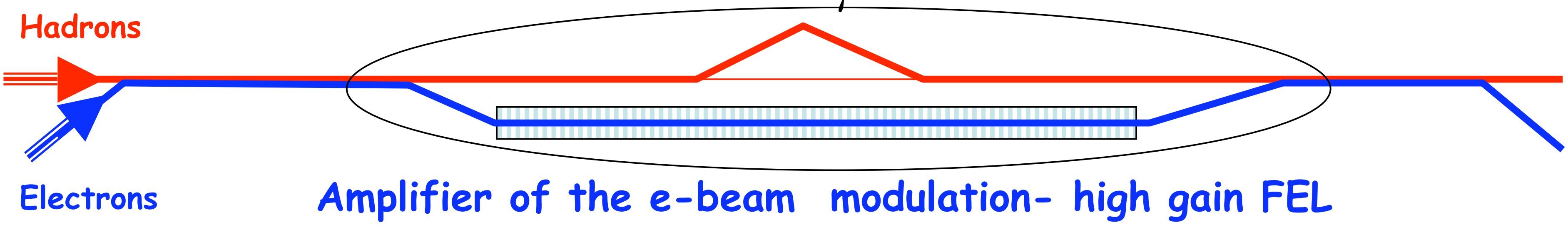
$$r_{//,lab} \propto \frac{c\sigma_\gamma}{\gamma^2 \omega_{pe}} \qquad r_{//,lab}(.1\%) \propto 7 \cdot 10^{-5}[m]/\gamma$$

$$r_\perp \propto \frac{c\gamma\sigma_{\theta e}}{\omega_{pe}} \qquad r_\perp \sim 0.3mm$$

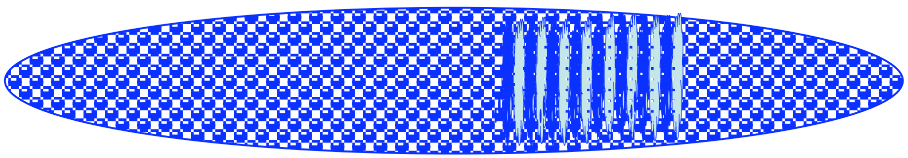
Each hadron generates modulation in the electron density with total charge of about minus charge of the hadron, Z

Longitudinal dispersion for hadrons, time of flight depends on its energy: $(T-T_o)\, v_o = -D\,(E-E_o)/E_o$

$$D = D_{free} + D_{chicane};\; D_{free} = \frac{L}{\gamma^2};\;\; D_{chicane} = l_{chicane} \cdot \theta^2$$



$$\lambda = \frac{\lambda_w}{2\gamma^2}\left(1 + a_w^2\right) \qquad L_{Go} = \frac{\lambda_w}{4\pi\rho\sqrt{3}} \qquad L_G = L_{Go}(1+\Lambda)$$



Electron density modulation is amplified in the FEL and made into a train with duration of $N_c \sim L_{gain}/\lambda_w$ alternating hills (high density) and valleys (low density) with period of FEL wavelength λ. Maximum gain for the electron density of HG FEL is ~ 10^3.

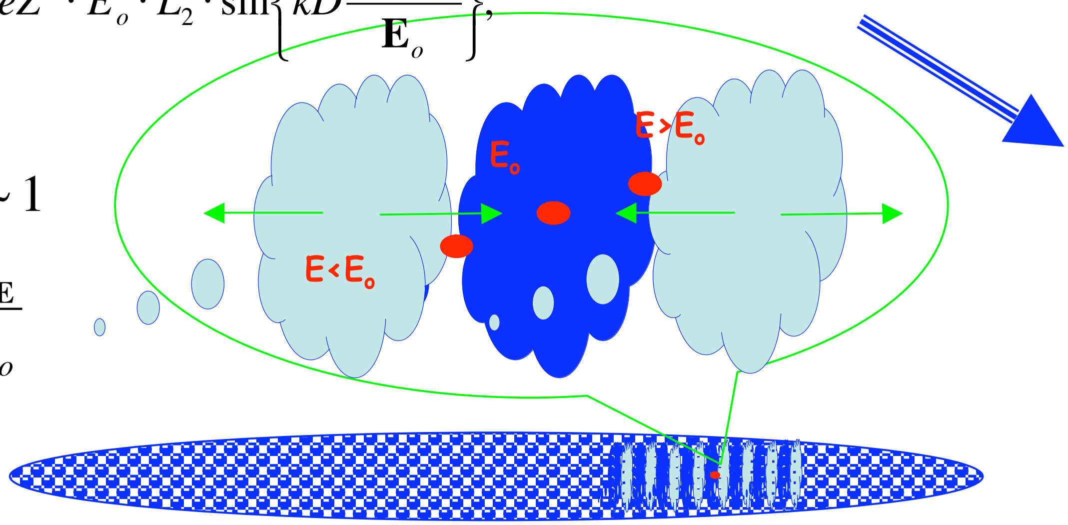
$$v_{group} = (c + 2v_{//})/3 = c\left(1 - \frac{1+a_w^2}{3\gamma^2}\right) = c\left(1 - \frac{1}{2\gamma^2}\right) + \frac{c}{3\gamma^2}\left(1 - 2a_w^2\right) = v_{hadrons} + \frac{c}{3\gamma^2}\left(1 - 2a_w^2\right)$$

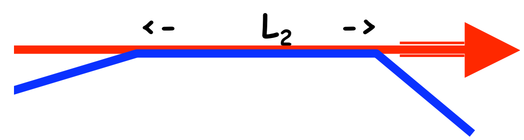
A hadron with central energy (E_o) phased with the hill where longitudinal electric field is zero, a hadron with higher energy ($E>E_o$) arrives earlier and is decelerated, while hadron with lower energy ($E<E_o$) arrives later and is accelerated by the collective field of electrons

$$\Delta \mathbf{E} = -eZ^2 \cdot E_o \cdot L_2 \cdot \sin\left\{ kD \frac{\mathbf{E}-\mathbf{E}_o}{\mathbf{E}_o} \right\};$$

$$kD\sigma_\varepsilon \sim 1$$

$$\sigma_\varepsilon = \frac{\sigma_\mathbf{E}}{\mathbf{E}_o}$$





$$\zeta_{CEC} = -\frac{\Delta \mathbf{E}}{\mathbf{E}-\mathbf{E}_o} \approx \frac{e \cdot E_o \cdot L_2}{\gamma_o m_p c^2 \cdot \sigma_\varepsilon} \cdot \frac{Z^2}{A}$$

Analytical formula for damping decrement

- 1/4 of plasma oscillation in region 1 with a clamp of electrons with the charge -Ze is formed
- longitudinal extend of the electron clamp is well within $\lambda_o/2\pi$
- gain in SASE FEL* is $G \sim 10^3$
- electron beam is wider than $2\gamma_o\lambda_o$ - it is 1D field
- Length of the region 2 is equal to beta-function

After the FEL charge modulation is -G*Ze

$$A_\perp = 2\pi\beta_\perp\varepsilon_n/\gamma_o$$

i.e. the charge density in CM frame can be written as

$$\rho = \frac{k}{2\gamma_o}\frac{G\cdot Z\cdot e}{A_\perp}\cdot\sin(kz/2\gamma_o)$$

CM frame

$$divE \cong kE_z/2\gamma_o = 4\pi\rho;$$

$$E_z = Z\cdot E_o\cdot\sin(kz/2\gamma_o); \quad E_o = \frac{2G\cdot e}{\beta_\perp\varepsilon_n}\gamma_o$$

Longitudinal electric field is the same in the lab and CM frames

$$\zeta_{CEC} = 2G\cdot\frac{r_p}{\sigma_\varepsilon\varepsilon_n}\cdot\frac{L_2}{\beta_\perp}\cdot\frac{Z^2}{A}$$

Electron bunches are usually much shorter that the hadron bunches and cooling time for the entire bunch is proportional to the bunch-lengths ratios

$$\zeta_{bunch} = \zeta_{CEC}\frac{\sigma_{\tau,e}}{\sigma_{\tau,h}}$$

Note that damping decrement does not depend on the energy of particles !
p in RHIC? Tevatron ? LHC ?

I. Modeling the problem of the modulator:
Ion can be described as a straight trajectory:

$$\vec{r}_i = \vec{r}_o + \vec{\mathrm{v}}_o t \qquad (1)$$

Initial distribution of electrons:

$$N_e \cdot f_o(\vec{r},\vec{\mathrm{v}});\ \iint f_o(\vec{r},\vec{\mathrm{v}})d\vec{r}d\vec{\mathrm{v}} = 1 \qquad (2)$$

Vlasov equation

$$\frac{\partial f_e}{\partial t} + \frac{\partial f_e}{\partial \vec{\mathrm{v}}}\cdot\frac{d\vec{\mathrm{v}}}{dt} + \frac{\partial f_e}{\partial \vec{r}}\cdot\vec{\mathrm{v}} = 0;\quad n_e = N_e\int f_e(\vec{r},\vec{\mathrm{v}})d\vec{\mathrm{v}}^3$$

$$\frac{d\vec{p}}{dt} = m\frac{d\vec{\mathrm{v}}}{dt} = e\vec{E};\quad div\vec{E} = 4\pi eZ\delta\left(\vec{r}-\vec{r}_i(t)\right) - 4\pi e n_e\left(\vec{r},t\right) \qquad (3)$$

Fully dimensionless equations of motion:

$$\frac{\partial f_e}{\partial \tau} + \frac{\partial f_e}{\partial \vec{v}}\cdot\vec{g} + \frac{\partial f_e}{\partial \vec{\rho}}\cdot\vec{v} = 0;\ \vec{g} = \frac{e\vec{E}}{m\omega_p{}^2 s};$$

$$\left(\vec{\nabla}_n\cdot\vec{g}\right) = \frac{Z}{s^3 n_e}\delta\left(\vec{\rho}-\vec{\rho}_i(t)\right) - \int f_e d\vec{v}^3;\quad \vec{\nabla}_n \equiv \partial_{\vec{\rho}}. \qquad (9)$$

Dimensionless time naturally comes from plasma frequency $\tau = \omega_p t$.

Velocities can be normalized to σ_{v_z},

while all dimensions can be normalized to longitudinal Debye radius $s = \sigma_{\mathrm{v}_z}/\omega_p$. Thus,

$$t = \tau/\omega_p;\quad \vec{\mathrm{v}} = \vec{v}\sigma_{\mathrm{v}_z};\quad \vec{r} = \vec{\rho}\sigma_{\mathrm{v}_z}/\omega_p;$$

$$\omega_p^2 = \frac{4\pi e^2 n_e}{m}$$

Independent parameters to vary:

Velocities:

electrons: ratio of transverse to longitudinal velocity spread: $R = \dfrac{\sigma_{\mathrm{v}_\perp}}{\sigma_{\mathrm{v}_z}}$;

ion: $Z = \dfrac{\mathrm{v}_{iz}}{\sigma_{\mathrm{v}_z}};\ T = \dfrac{\mathrm{v}_{ix}}{\sigma_{\mathrm{v}_\perp}};\ \mathrm{v}_{ix} = \sigma_{\mathrm{v}_z}\cdot T\cdot R;$

Simulations

Modulator - VORPAL (exists)

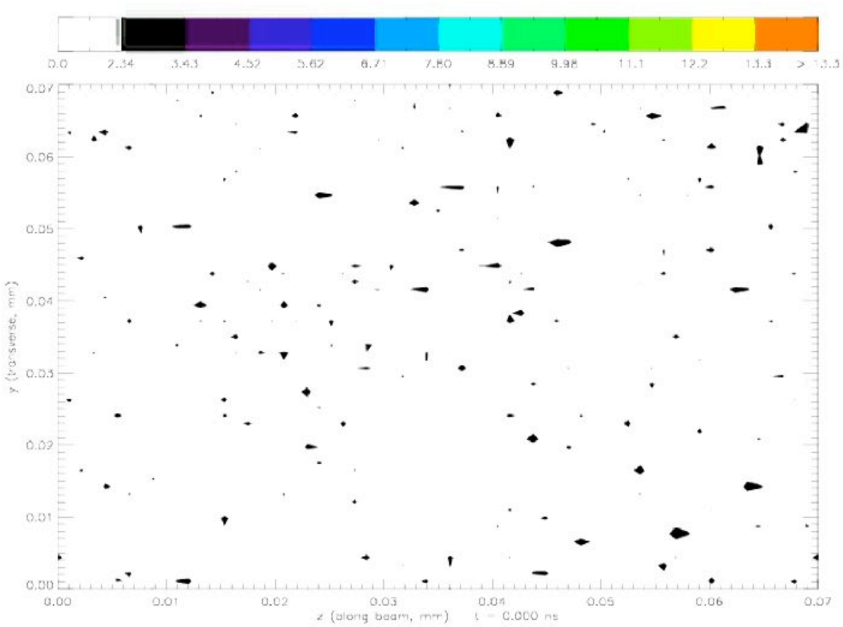
FEL amplifier - Genesis3 (exists)

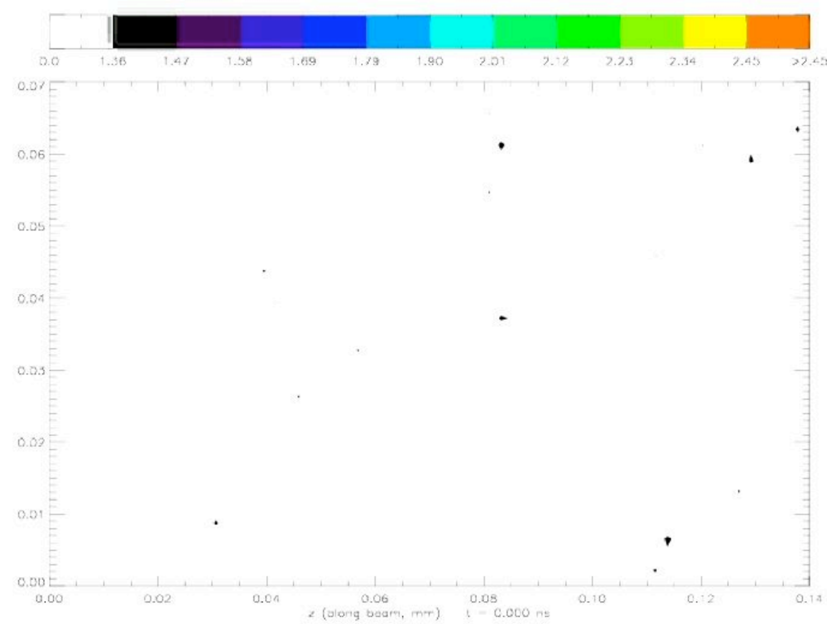
Kicker - VORPAL

©Tech-X

Parameter #	Value	Comments
Relative ion velocity	3.0E5 m/sec	The ion is moving in the z direction (parallel to the beam)
Interaction Distance	10 m	In the lab frame.
Interaction Time (tau)	3.1E-10 sec	In the beam frame.
Box Size (z)	1.4E-4 m	This is the length of the simulation along the horiontal (z) axis. This is about 50% larger than vrel*tau = 9.3E-5 m.
Box Size (x)	7.0E-5 m	This is the length of the simulation along the vertical (x) axis.
Density Plot Slice (y)	2.1E-6 m	A thin slice around y=0 was taken to create the density plot. In the actual simulation the y Box Size is the same as the x Box Size.
Electron Density	8.10E+15 e-/m^3	

Vx (rms) = Vy (rms) = 2.8E4 m/s, Vz (rms) 9.0E3 m/s





Note: Given the density and box size above, the number of actual electrons in the slice shown is only_8.10E15 e-/m^3)(5.3E-5 m)(2.1E-6 m)(1.0E-4 m) = 90_n order to get reasonable statistics, each electron was split into N microparticles having the same charge/mass ratio. In the simulations, N=3500. An individual wake behind a gold ion will be much noisier

BROOKHAVEN NATIONAL LABORATORY

RHIC

$$F(z) = \int f_e(\vec{\rho} - \hat{z}\cdot Z\tau, \vec{v}, \tau)\, d\vec{v}^3 dxdy$$

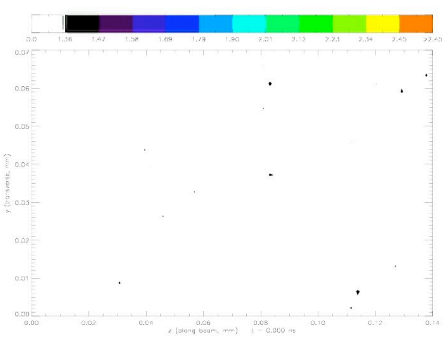
$$V_z(z) = \int v_z f_e(\vec{\rho} - \hat{z}\cdot Z\tau, \vec{v}, \tau)\, d\vec{v}^3 dxdy$$

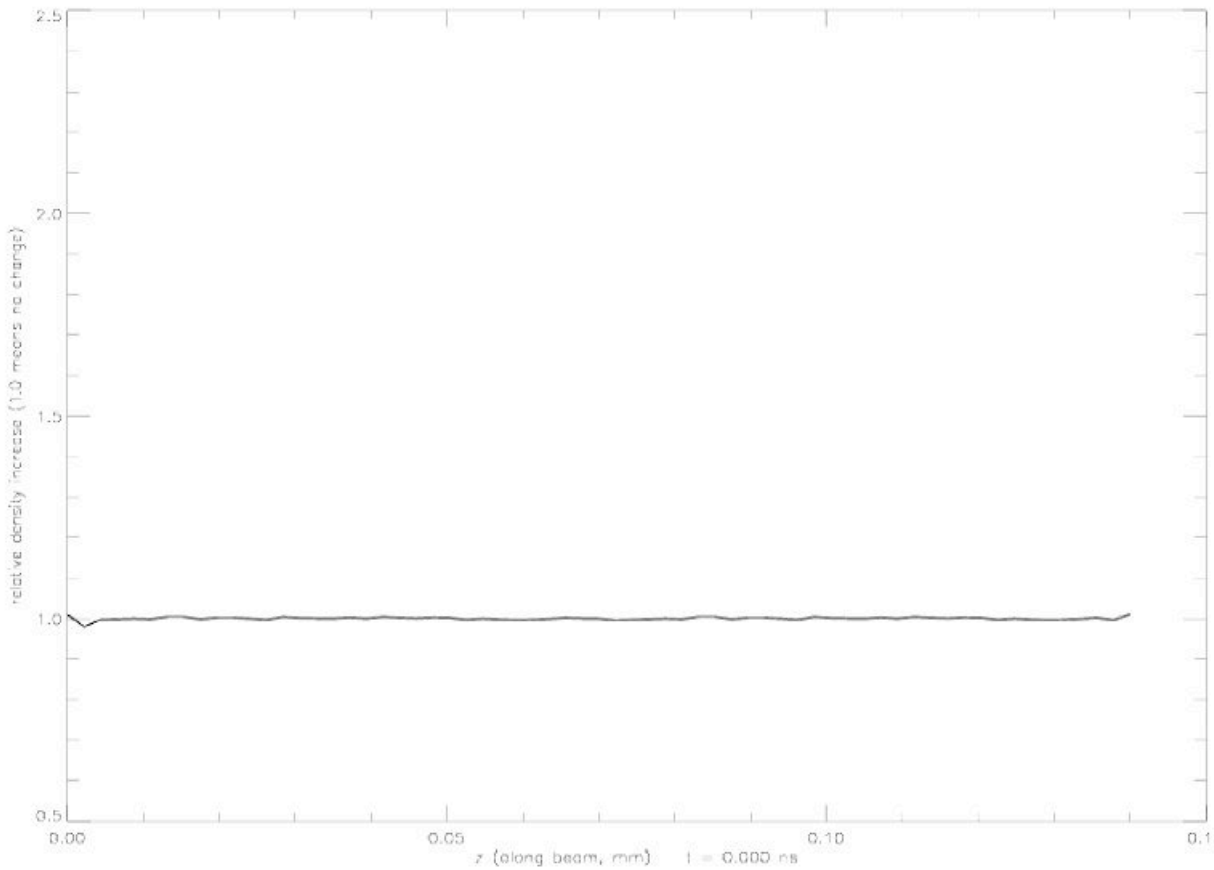
$$F(x) = \int f_e(\vec{\rho} - \hat{x}\cdot T\cdot R\cdot \tau, \vec{v}, \tau)\, d\vec{v}^3 dzdy$$

$$F(y) = \int f_e(\vec{\rho}, \vec{v}, \tau)\, d\vec{v}^3 dzdx$$

$$A(k) = \int F(z)\cdot \exp(ikz)\, dz$$

Observables: example is for F(z)

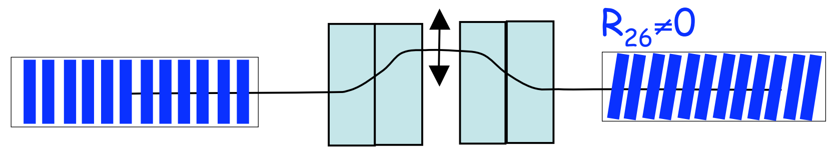




Transverse cooling

- Transverse cooling can be obtained by using coupling with longitudinal motion via transverse dispersion
- Sharing of cooling decrements is similar to sum of decrements theorem for synchrotron radiation damping, I.e. decrement longitudinal cooling can be split into appropriate portions to cool both transversely and longitudinally: $J_s+J_h+J_v=J_{CEC}$
- Vertical (better to say the second eigen mode) cooling is coming from t-coupling

Non-achromatic chicane installed at the exit of the FEL before the kicker section turns the fronts of the charged planes



$$\delta z = -R_{26} \cdot x$$

$$\Delta \mathbf{E} = -eZ^2 \cdot E_o \cdot L_2 \cdot$$
$$\sin\left\{k\left(D\frac{\mathbf{E}-\mathbf{E}_o}{\mathbf{E}_o} + R_{16}x' - R_{26}x + R_{36}y' + R_{46}y\right)\right\};$$

$$\Delta x = -\eta \cdot eZ^2 \cdot E_o \cdot L_2 \cdot kR_{26}x + ...$$

$$J_x(\max) \cong \frac{\eta\sigma_\varepsilon}{\sigma_x} J_{CEC}$$

Effects of the surrounding particles

Each charged particle causes generation of an electric field wave-packet proportional to its charge and synchronized with its initial position in the bunch

$$E_z = \sum_{i,hadrons} Z \cdot E_o(v_o t - z + z_j) \cdot \sin k(v_o t - z + z_i) - \sum_{j,electrons} E_o(v_o t - z + z_j) \cdot \sin k(v_o t - z + z_j)$$

Evolution of the RMS value: resembles stochastic cooling!

Best cooling rate achievable is ~ $1/\tilde{N}$, $\tilde{N}$ is effective number of hadrons in coherent sample ($N_c\lambda$); cooling "faster" will only

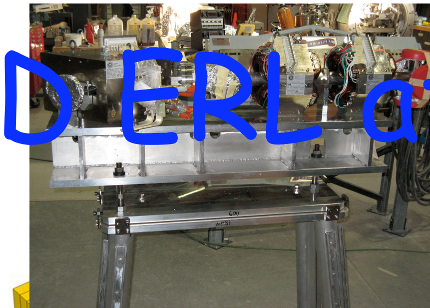
$$\frac{d\sigma_E^2}{dn} = -2\Delta \frac{kD}{\mathbf{E}_o}\sigma_E^2 + \frac{1}{2}\Delta^2 \tilde{N}$$

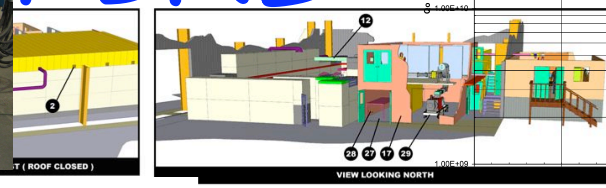
$$\Delta = eZ^2 \cdot L_2 \cdot E_o; \tilde{N} = \tilde{N}_h + \tilde{N}_e / Z^2$$

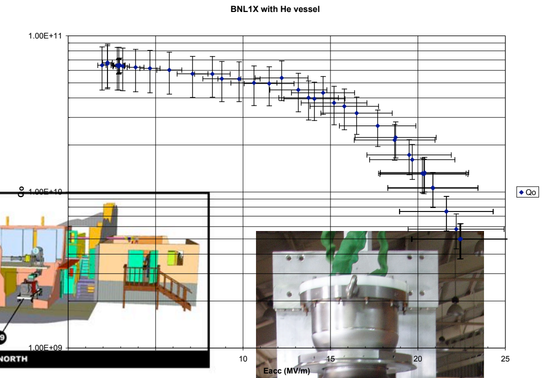
$$\frac{\sigma_E^2}{\mathbf{E}^2_o} = \frac{1}{4kD} \cdot \frac{\Delta}{\mathbf{E}_o} \cdot \tilde{N}$$

$$J_{CEC} = \frac{\Delta}{2\sigma_E} = \frac{2}{\tilde{N}}\left(kD\sigma_\varepsilon\right) \sim \frac{1}{\tilde{N}}$$

R&D ERL at BNL







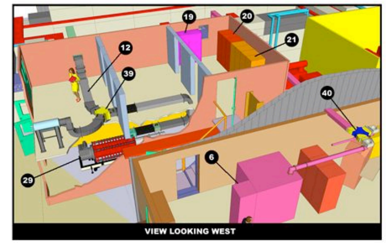
E_{inj} =2.5-.3.5 MeV

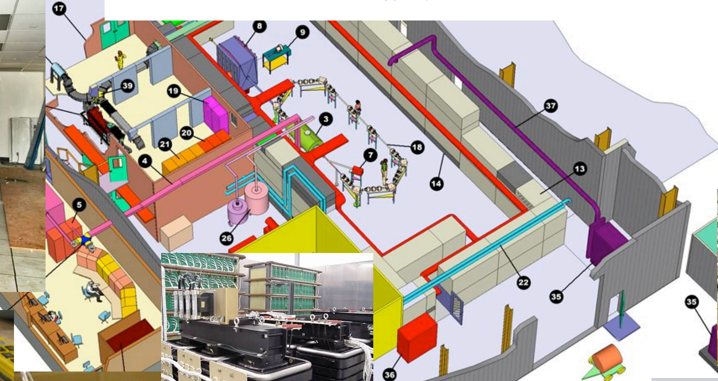
E_{total} = 25 MeV, I_{max} = 0.5 A

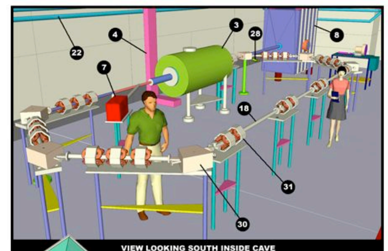
ε_n ~ 2 mm mrad @ 1.4 nC

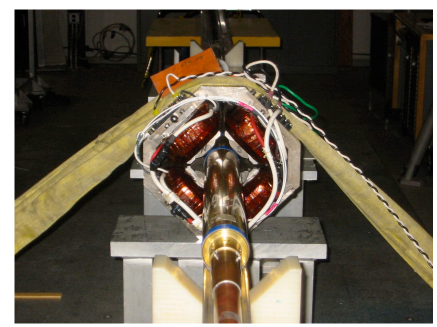
Single Loop, SRF Gun

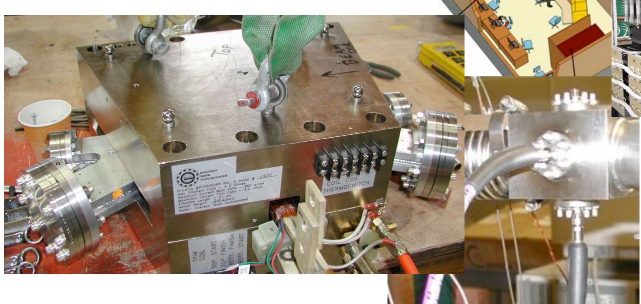
5 cell SRF linac, 703.75 MHz

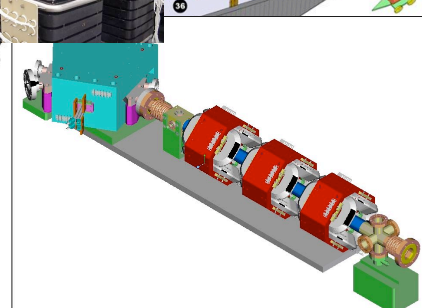


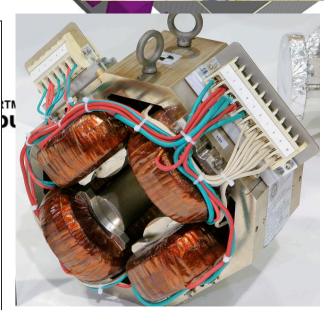








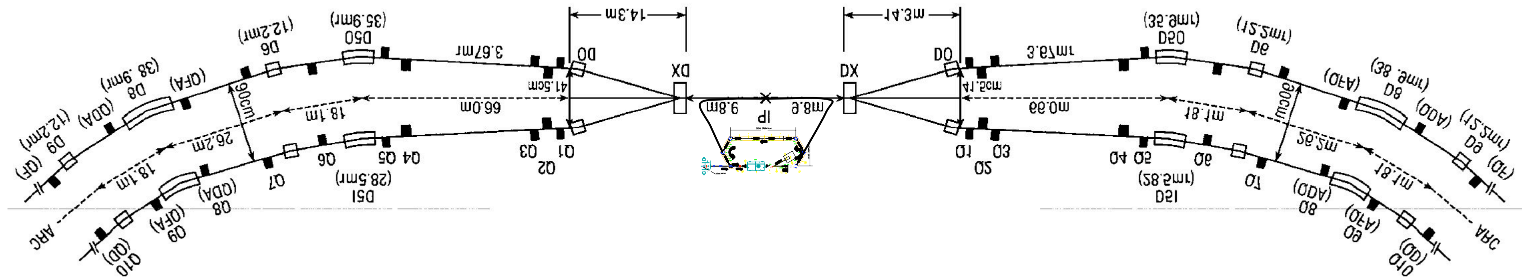


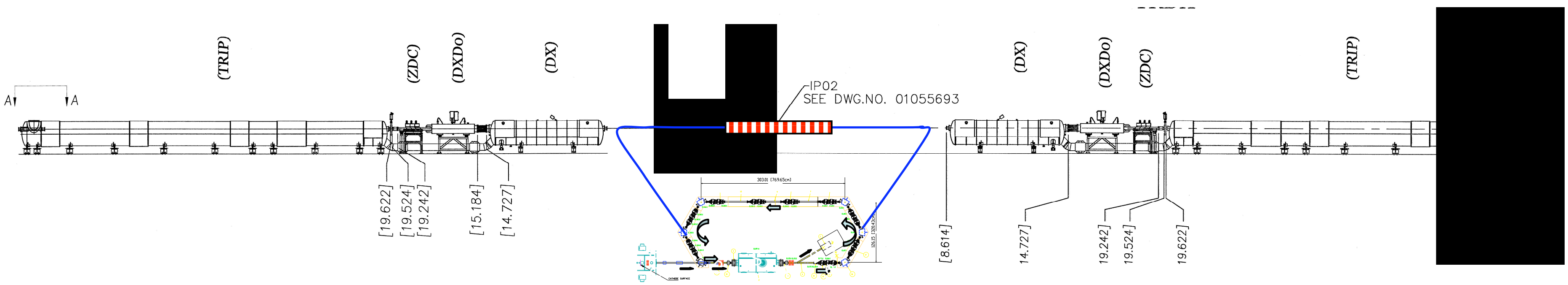


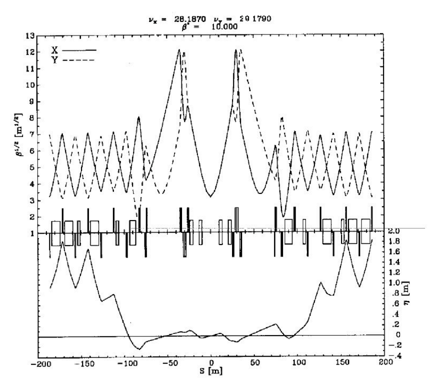
BROOKHAVEN NATIONAL LABORATORY

RHIC

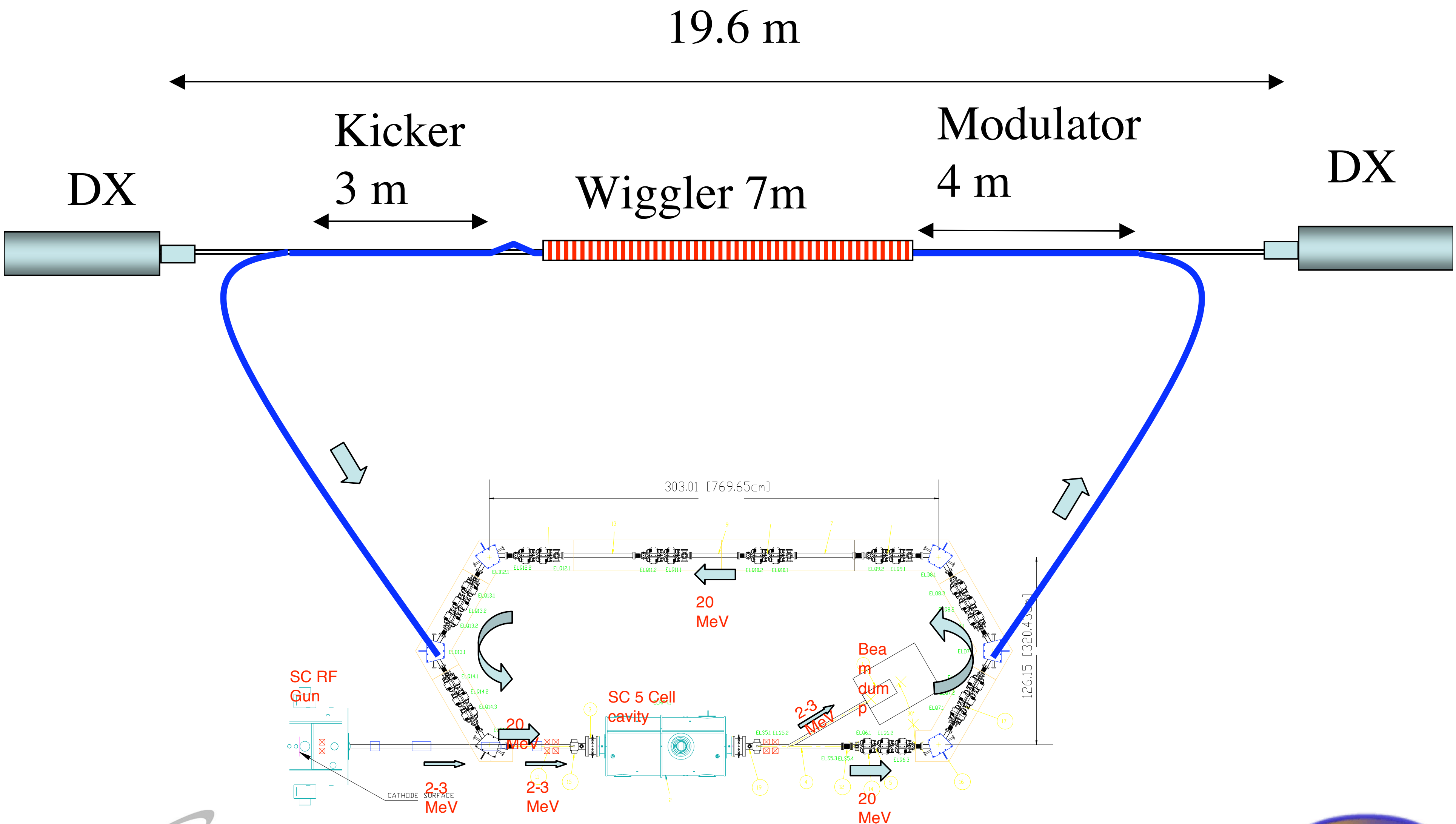
IR-2 for proof-of-principle for CEC

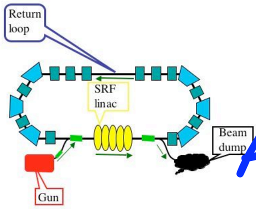






IR-2 for proof-of-principle for CEC





Test using BNL R&D ERL: Au ions in RHIC with 40 GeV/n, L_{cooler} = 14 m

N per bunch	$2\ 10^9$	Z, A	79, 197
Energy Au, GeV/n	40	γ	42.63
RMS bunch length, nsec	3.2	Relative energy spread	0.037%
Emittance norm, μm	2.5	$\beta_\perp$, m*	8
Energy e^-, MeV	21.79	Peak current, A	60
Charge per bunch, nC	5 (or 4 x 1.4)	Bunch length, RMS, psec	83
Emittance norm, μm	5 (4)	Relative energy spread	0.15%
$\beta_\perp$, m	5	L_1 (lab frame) ,m	4
ω_{pe}, CM, Hz	$5.03\ 10^9$	Number of plasma oscillations	0.256
$\lambda_{D\perp}$, μm	611	$\lambda_{D\|\|}$, μm	3.3
λ_{FEL}, μm	**18**	**λ_w, cm**	**5**
a_w	**0.555**	**L_{Go}, m**	**0.67**
Amplitude gain =150, L_w , m	**6.75 (7)**	**L_{G3D}, m**	**1.35**
L_2 (lab frame) ,m	**3**	**Cooling time, local, minimum**	**0.05 minutes**
N_{turns}, $\tilde{N}$, 5% BW	$8\ 10^6 > 6\ 10^4$	**Cooling time, beam, min**	**2.6 minutes**

It is always easy to make it longer, if needed.

250 GeV polarized protons in RHIC, L_{cooler} ~ 60m

N per bunch	$2\ 10^{11}$	Z, A	1, 1
Energy Au, GeV/n	250	γ	266.45
RMS bunch length, nsec	1	Relative energy spread	0.04%
Emittance norm, μm	2.5	$\beta_\perp$, m	10
Energy e^-, MeV	136.16	Peak current, A	100
Charge per bunch, nC	5	Bunch length, nsec	0.2
Emittance norm, μm	3	Relative energy spread	0.04%
$\beta_\perp$, m	10	L_1 (lab frame) ,m	30
ω_{pe}, CM, Hz	$4.19\ 10^9$	Number of plasma oscillations	0.25
$\lambda_{D\perp}$, μm	1004	$\lambda_{D\|\|}$, μm	0.17
λ_{FEL}, μm	**0.5**	**λ_w, cm**	**5**
a_w	**0.648**	**L_{Go}, m**	**0.87**
Amplitude gain =100, L_w , m	**13 (-> 15)**	**L_{G3D}, m**	**1.22**
L_2 (lab frame) ,m	10	**Cooling time, local, min**	**1.96**
$N_{min\ turns}$ or $\tilde{N}$ in 10% BW	$6.7\ 10^6 > 5.9\ 10^6$	**Cooling time, beam, min**	**49.2**

Conclusions

- Coherent electron cooling is very promising method for high energy hadron and lepton-hadron colliders
- It takes full advantage of high gain FELs based on high brightness ERLs which are under development at C-AD
- **Proof of principle experiment of cooling Au ions in RHIC at ~ 40 GeV/n is feasible with existing R&D ERL**
- Cooling 100 GeV/n ions and 250 GeV protons in RHIC seems to be straight forward